

PETROLOGICAL STUDIES OF THE YAMATO METEORITES PART 2. PETROLOGY OF THE YAMATO METEORITES

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Abstract: The result of the mineralogical and petrological studies of the Yamato (a), Yamato (b), Yamato (c), Yamato (d) and Yamato (g) meteorites is summarized as follows. The Yamato (a) meteorite is distinctly chondritic, and belongs to enstatite chondrite. This meteorite is metal- and sulfide-rich, and its silicate phase is composed mainly of nearly pure enstatite and clinoenstatite. The peculiar mineral composition shows that this meteorite was formed under an extremely reducing condition. The morphology and petrography of chondrules in the Yamato (a) meteorite suggest that they were formed by rapid quenching of liquid droplets. The Yamato (b) meteorite is nearly monomineralic consisting of bronzite, without chondrule. According to PRIOR's (1920) classification, the Yamato (b) meteorite belongs to hypersthene achondrite in calcium-poor achondrites. The Yamato (c) meteorite is chondritic, and is composed mainly of olivine with a fair amount of magnetite. This meteorite belongs to type III carbonaceous chondrite, and may have experienced an oxidative environment. The Yamato (d) meteorite is composed mainly of olivine, bronzite, nickel-iron and troilite, and belongs to olivine-bronzite chondrite. The Yamato (g) meteorite consists of olivine, bronzite and nickel-iron, and is referred to olivine-bronzite chondrite.

1. Classification of the Yamato Meteorites

In the light of the mineralogical descriptions given in Part 1, all the samples of the Yamato meteorites are assigned to stony meteorites. Microscopic observations of their structures reveal that the Yamato (a), Yamato (c), Yamato (d) and Yamato (g) meteorites are chondrites, and the Yamato (b) meteorite is achondrite.

Yamato (a) meteorite: The Yamato (a) meteorite is chondrite with unique mineralogical features. Its silicate phases are composed mainly of nearly pure enstatite and clinoenstatite, and the occurrence of niningerite, daubreelite, graphite and Si-bearing kamacite directly shows that this meteorite is enstatite chondrite which was formed under an extremely reduced condition. In enstatite chondrite, it is notable that even the lithophillic elements such as Ca, Mg, Cr, Mn and Ti show chalcophillic property (ALLEN and MASON, 1973). They are present forming or entering into sulfide minerals such as oldhamite (CaS), niningerite ((Mg, Fe, Mn, Ca, Cr)S), ferroan alabandite ((Mn, Fe)S), daubreelite (FeCr₂S₄) and Ti-bearing troilite (KEIL, 1968).

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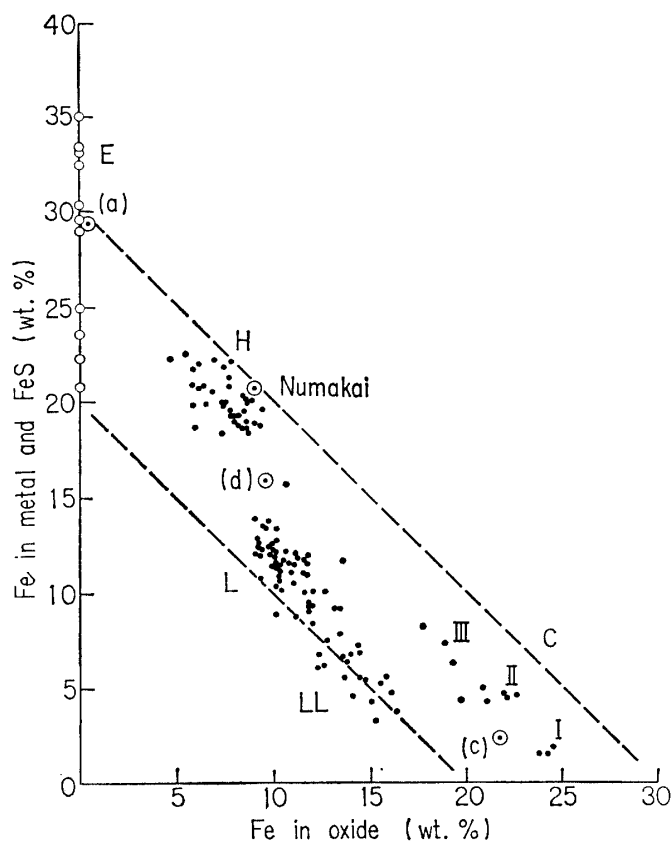


Fig. 1. Urey-Craig diagram (modified version of the diagram by REID and FREDRIKSSON, 1967). (a), (c) and (d) indicate the Yamato (a), (c) and (d) meteorites, respectively.

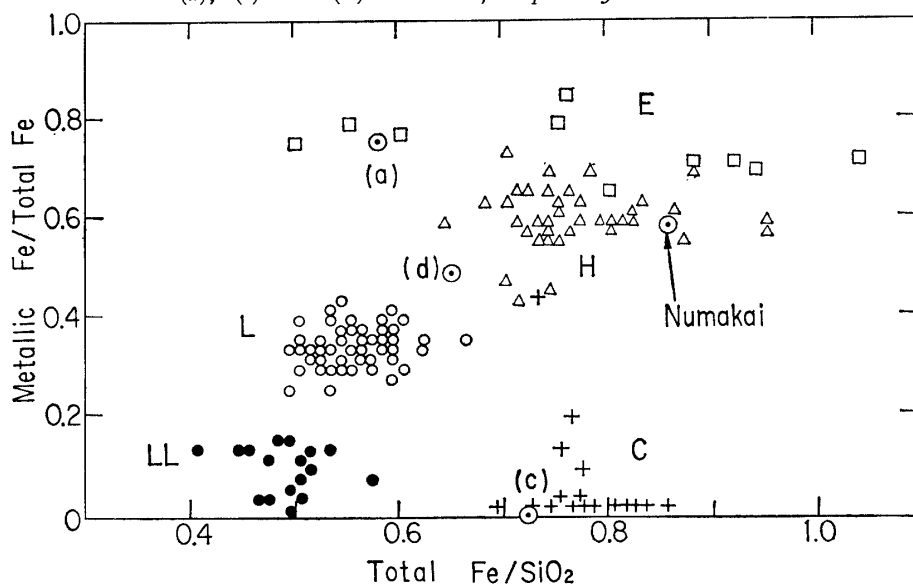


Fig. 2. Plot of metallic Fe/total Fe versus total Fe/SiO₂ in wt. % (modified version of the diagram by VAN SCHMUS and WOOD, 1967). (a), (c) and (d) indicate the Yamato (a), (c) and (d) meteorites, respectively.

The presence of Si-bearing nickel-iron in enstatite chondrite was first detected by PRIOR (1916), and later investigated by RINGWOOD (1960), KEIL and ANDERSEN (1965), and KEIL (1968).

Urey-Craig diagram in Fig. 1 distinctly shows that the Yamato (a) meteorite belongs to the enstatite chondrite group, and the same result by VAN SCHMUS and WOOD (1967) is shown in Fig. 2. These results should be ascribed to the chemical nature of enstatite chondrites where most of iron is present in the metallic and sulfide forms, and oxidized iron is extremely low in content. REED *et al.* (1960) showed that several trace elements, especially bismuth, lead and thallium, are highly concentrated in enstatite chondrites compared with ordinary chondrites. The contents of bismuth, lead and thallium of the Yamato (a) meteorite are 0.280, 2.240 and 0.240 ppm, respectively (HINTENBERGER *et al.*, 1973). According to REED *et al.* (1960), Abee meteorite has 2.56 ppm Pb and 0.125 ppm Tl, and Indarch meteorite has 0.08 ppm Bi, 4.20 ppm Pb and 0.084 ppm Tl. These enstatite chondrites, including the Yamato (a) meteorite, have remarkably high Bi, Pb and Tl contents in comparison with their average compositions in ordinary chondrites, having 0.003 ppm Bi, 0.15 ppm Pb and 0.0004 ppm Tl.

MASON (1966) investigated 15 enstatite chondrites, and proposed to divide them into two subgroups by their mineralogy and structures. One of the subgroups is the iron-rich enstatite chondrite, represented by Adhi Kot, Indarch and Saint Sauveur meteorites. It is chondritic and fine-grained, and its silicate phases are composed mainly of clinoenstatite (sometimes with a subordinate amount of enstatite) and silica minerals. The other subgroup is the iron-poor enstatite chondrite, represented by St. Marks meteorite. It is coarse-grained and poorly chondritic or non-chondritic. Its silicate phases are composed mainly of enstatite and plagioclase (oligoclase). These subgroups correspond to type I (unrecrystallized enstatite chondrite) and type II (recrystallized enstatite chondrite) of ANDERS (1964).

KEIL (1968) divided enstatite chondrites into three subgroups, type I, intermediate type, and type II. The intermediate type was defined as a transitional group between type I and type II. According to KEIL (1968), these subgroups correspond respectively to E4, E5 and E6 of the chemical and petrologic types by VAN SCHMUS and WOOD (1967). The structural differences among these subgroups are correlated to the mineral compositions and chemical compositions of minerals. Table 1 shows the minerals found in each type of the enstatite chondrite and the Yamato (a) meteorite. It is especially notable that olivine is present only in the unrecrystallized enstatite chondrite (type I). Cristobalite occurs in the relatively unrecrystallized chondrites in comparison with other silica polymorphs, quartz and tridymite. Niningerite also occurs in such chondrites. It is suggested that the Yamato (a) meteorite can be assigned to the unrecrystallized enstatite chondrite (type I), judging from its distinct chondritic structure shown in Fig. 3 of Part 1 and its mineralogy in Table 1. On the other hand, the chemical compositions of individual minerals show slight differences corresponding to the meteorite types. Pyroxene of the Yamato (a) meteorite has a nearly similar tendency to that of type I enstatite chondrites in regard to minor constituents,

Table 1. Mineral constituents of the enstatite chondrites* and the Yamato (a) meteorite.

	Type I	Intermediate	Type II	Yamato (a)
Clinoenstatite	+	+	+	+
Enstatite	+	+	+	+
Olivine	+			+
Albite	+	+		
Oligoclase			+	
Quartz		+	+	
Tridymite	+		+	
Cristobalite	+	+		+
Sinoite			+	
Roedderite	+			
Kamacite	+	+	+	+
Taenite	+		+	
Gold			+	
Copper			+	
Troilite	+	+	+	+
Daubreelite	+	+	+	+
Oldhamite	+	+	+	(+)**
Ferroan alabandite			+	
Niningerite	+	+		+
Sphalerite	+	+	+	(+)**
Djerfisherite	+	+		
Schreibersite	+	+	+	+
Perryite	+		+	+
Cohenite	+	+	+	
Lawrencite	+			

* Referred to KEIL (1968).

** Probably present.

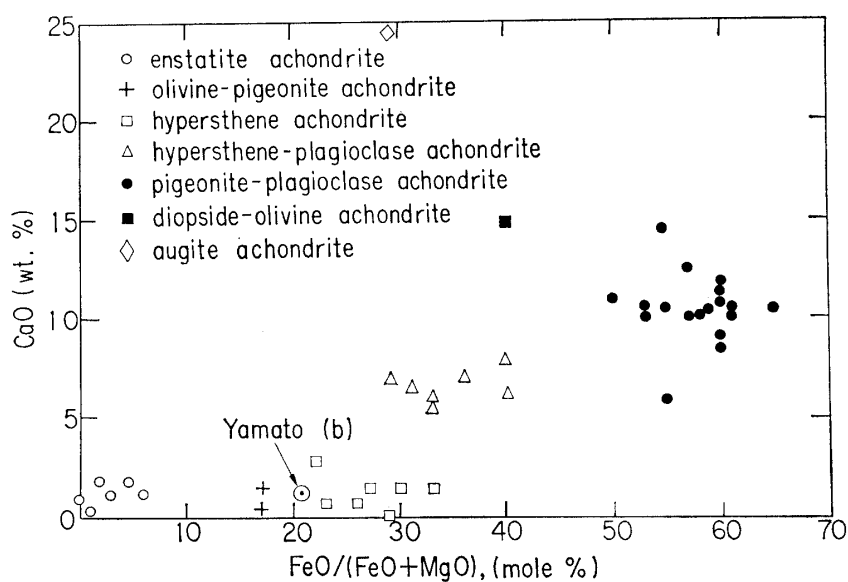


Fig. 3. Plot of CaO (wt. %) versus $FeO/(FeO+MgO)$ (mole %) for achondrites (modified version of the diagram by MASON, 1962a). CaO-poor achondrites and CaO-rich ones are distinguishable.

especially FeO and MnO. Ferroan alabandite, (Fe, Mn)S (KEIL, 1968), and sinoite, $\text{Si}_2\text{N}_2\text{O}$ (ANDERSEN *et al.*, 1964), characteristic of recrystallized enstatite chondrites (type II) could not be found in the Yamato (a) meteorite.

Yamato (b) meteorite: The Yamato (b) meteorite lacks chondrules in its entire mass, its structure closely resembling that of terrestrial rocks. These features are characteristic of achondrites. PRIOR's (1920) classification of achondrites is primarily based on their calcium contents, that is, the calcium-poor achondrites are 0-3 wt. % in CaO and the calcium-rich ones are 5-25 wt. % in CaO. The Yamato (b) meteorite belongs to the calcium-poor achondrite because of 1.21 wt. % CaO in its bulk chemical composition. The subgroups of achondrites are best illustrated by plotting CaO content (wt. %) versus $\text{FeO}/(\text{FeO}+\text{MgO})$ (mole ratio) as shown in Fig. 3. The result shows that the Yamato (b) meteorite is hypersthene achondrite of PRIOR (1920). From the mineralogical standpoint also, this meteorite can belong to the same subgroup, because more than 90 vol. % of its main mass is occupied by bronzite ($\text{En}_{74}\text{Fs}_{25}$). The Yamato (b) meteorite also agrees with the bronzite achondrite of KEIL (1969) who proposed the name after the mineralogical term of the corresponding orthopyroxene. MASON (1963), investigating 8 hypersthene achondrites, showed that the orthopyroxenes of this kind of meteorites ranged from 25 to 27% Fs in molar composition, and that the exsolution lamellae of clinopyroxene, probably diopside, were present in the orthopyroxene of several hypersthene achondrites. Though bronzite of the Yamato (b) meteorite has no exsolution lamellae, independent clinopyroxene grains which are probably diopside are present in a minor amount. Olivine, a very rare mineral in hypersthene achondrites, is not present in the Yamato (b) meteorite. The Yamato (b) meteorite does not show a brecciated structure which is common in hypersthene achondrites and enstatite achondrites (MASON, 1962a, 1963).

Yamato (c) meteorite: The Yamato (c) meteorite is chondritic, and its dark-colored matrix and strongly magnetic property are due to the presence of a fair amount of magnetite.

Fig. 1 and Fig. 2 show that the Yamato (c) meteorite belongs to carbonaceous chondrite, with an extremely low content of metallic iron and rich oxidized iron. Carbonaceous chondrites are quite distinct from other meteorites on account of the presence of organic matter and hydrous minerals in the formers. WILK (1956) divided carbonaceous chondrites into three subtypes on the basis of chemical compositions. The average contents of carbon, sulfur and H_2O systematically decrease from type I through type II to type III carbonaceous chondrites. These chemical differences are correlated to the mineralogical compositions and structures of the respective types. Type I carbonaceous chondrites have no chondrule and are composed predominantly of amorphous hydrous magnesium silicates with subordinate amounts of magnetite, troilite, native sulfur and sulfate minerals (BOSTRÖM and FREDRIKSSON, 1966; DUFRESNE and ANDERS, 1962; MASON, 1962b). Type II carbonaceous chondrites consist mainly of serpentine or chlorite with subordinate amounts of olivine, pyroxene, magnetite, and sulfate and sulfide minerals (DUFRESNE and ANDERS, 1962; MASON, 1962b; WOOD, 1967). The Yamato (c) meteorite is differ-

ent from either type I or type II in mineralogy, and belongs to type III consisting predominantly of olivine and lacking hydrous silicate minerals. MASON (1962a) placed type III carbonaceous chondrites in the olivine-pigeonite chondrite group together with non-carbonaceous olivine-pigeonite chondrites. On the other hand, KEIL and FREDRIKSSON (1964) and KEIL (1969) described them as high-iron low-metal (HL) group chondrites. The presence of pentlandite is characteristic of the Yamato (c) meteorite. This mineral is found in chondrites containing magnetite and almost lacking metallic nickel-iron (MASON, 1962a; RAMDOHR, 1973). The high content of total nickel in this meteorite as shown in Table 2 of Part 1 is probably ascribed to the presence of pentlandite.

Yamato (d) and Yamato (g) meteorites: Both meteorites are rich in olivine as shown by their modal compositions (Tables 17 and 18 of Part 1). Orthopyroxene, a major mineral next to olivine, is bronzite in the both meteorites. Their mineralogical features are in good agreement with those of olivine-bronzite chondrites. Fig. 1, Fig. 2 and Fig. 4 also indicate that the Yamato (d) meteorite is high-iron group chondrite, that is, olivine-bronzite chondrite.

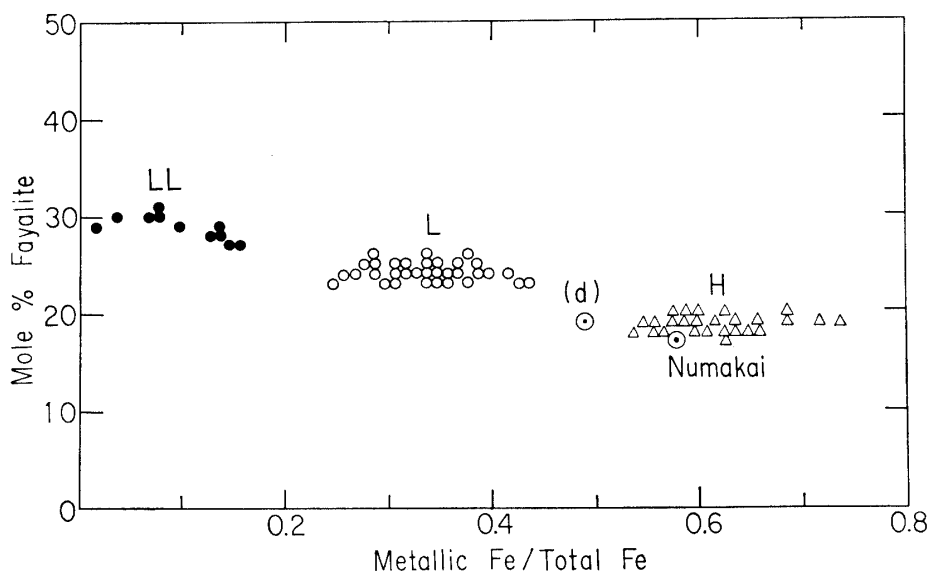


Fig. 4. Plot of fayalite content of olivine in mole % versus metallic Fe/total Fe in wt. % (modified version of the diagram by VAN SCHMUS and WOOD, 1967). (d) indicates the Yamato (d) meteorite.

2. Petrology of the Yamato Meteorites

2.1. Formation of chondrules

Chondrules are spheroidal and ellipsoidal materials characteristic of chondritic meteorites. They are generally composed of compact assemblage of minute pyroxene and olivine crystals, and they are not found in terrestrial rocks. The Yamato (a), Yamato (c), Yamato (d) and Yamato (g) meteorites contain chondrules in their matrices. The origin of chondrules has been extensively investigated by many

workers because of their peculiar features that can not be seen in other types of meteorites except chondrites and in the terrestrial matters. SORBY (1877) first proposed that chondrules has been derived from fused silicate droplets. This theorem is now widely accepted among meteoricists (for example, FREDRIKSSON and REID, 1965; WOOD, 1963), because of the common spheroidal shape of chondrules, their mineral compositions consisting mainly of ferromagnesian silicate minerals, and their internal structures which are similar to those of the quenched silicate melts.

The Yamato (a) enstatite chondrite is especially chondritic in comparison with the Yamato (c), Yamato (d) and Yamato (g) meteorites, and some chondrules in the Yamato (a) meteorite show several mineralogical features characteristic of rapidly cooled melts. Glass-bearing chondrules and cryptocrystalline ones are examples of such case. These facts show that chondrules were formed by rapid cooling of silicate droplets from high temperature as first pointed out by SORBY (1877). Fibrously radiating and elongated rod-like crystal growths of olivine and pyroxene are commonly found in the meteoritic chondrules, and they are ascribed to rapid crystallization from silicate melts. The Yamato (a) meteorite is rich in varieties of chondrule types, for example, cryptocrystalline chondrules (Fig. 6 of Part 1), microporphyritic chondrules composed of enstatite and clinoenstatite with or without olivine (Fig. 4 of Part 1), microporphyritic olivine chondrules, fibrously radiating or barred-type enstatite or clinoenstatite chondrules with or without olivine (Fig. 20 of Part 1) and so on. From the CIPW norms in Table 9 of Part 1, cryptocrystalline chondrules can be considered to be direct products solidified from a mixed solution approximately composed of orthopyroxene and olivine with minor amounts of normative albite, sodium metasilicate, diopside and ilmenite. The brown-colored grains in Table 9 of Part 1 are the same kind of materials as cryptocrystalline chondrules. Although these cryptocrystalline chondrules and brown-colored grains are present together in a single meteorite, it is interesting that their chemical and normative compositions vary from chondrule to chondrule and from grain to grain. Their cryptocrystalline structure shows that they were suddenly formed at such a fast cooling rate that olivine and pyroxene could not be crystallized out. Fibrous radiating and barred-type pyroxene chondrules are also produced by rapid quenching. Olivine in these kinds of chondrules is usually crystallized in subhedral forms with a reaction rim of orthopyroxene (probably enstatite). This fact suggests that the quenching of droplets took place with the rapid crystal growth of pyroxene after or during the reaction of early separated olivine with the residual liquid. The microporphyritic chondrules consisting of euhedral and subhedral olivine and pyroxene grains are also believed to have been formed by rapid cooling, because they usually have interstitial glass. The glass is a residual liquid survived the crystallization of magnesium-rich pyroxene and olivine, and it is consequently enriched with Na, K, Ca, Al and Si. Some glasses include minute dendritic crystallites which are often seen in terrestrial volcanic glass. The association of clinoenstatite and enstatite is usually observed in microporphyritic chondrules of the Yamato

(a) meteorite. Clinoenstatite which is usually present in polysynthetic twinning is probably formed by the inversion of protoenstatite, and enstatite is presumably formed by the inversion of clinoenstatite (BOYD and ENGLAND, 1965). The varying quantity of pyroxene and olivine grains from one chondrule to another shows that the composition of the original liquid varied from droplet to droplet. The various morphologies of silicate chondrules have features in common with the crystallization of supercooled metallic droplets (FEHLING and SCHEIL, 1962; BLANDER and ABDEL-GAWAD, 1969). The cryptocrystalline chondrules were probably formed from an extremely supercooled melt below the solidus temperature, indicating that the chemical composition of the crystallized solid phase directly corresponds to that of the original molten droplet, and that the solid phase is composed mainly of cryptocrystalline aggregate of olivine and pyroxene. The barred-type and radiating chondrules may have solidified from a relatively supercooled melt. Microporphyrific chondrules may have been originated from a little supercooled or nearly equilibrated state, and euhedral crystals crystallized from the melt. The Yamato (a) meteorite has an iron chondrule (Fig. 10 of Part 1) and a chondrule-like aggregate of kamacite, schreibersite, troilite and niningerite (Fig. 14 of Part 1). The Yamato (c) meteorite contains a few chondrule-like aggregates of magnetite, pentlandite and troilite (Fig. 41 of Part 1). Above all, the peculiar form of the iron chondrule in the Yamato (a) meteorite which consists of elongated, rod-like nickel-iron interstitially associated with plagioclase and clinopyroxene, suggests that the chondrule was formed by rapid cooling of a fused droplet of silicate-bearing metallic-iron. The granular chondrules composed of olivine grains in the Yamato (c) usually include minute opaque spheroids of magnetite, pentlandite and troilite (Fig. 38 of Part 1). A similar feature was often noticed in carbonaceous chondrites (WOOD, 1967). This is probably due to collision between metal droplets and silicate ones during the formation of chondrules. For example, the Yamato (c) meteorite has an olivine chondrule which encountered an opaque chondrule as shown in Fig. 42. The coexistence of silicate chondrules and metallic chondrules in a single meteorite, as seen in the Yamato (a) and Yamato (c) meteorites, may suggest that metals and silicates in the parent material of chondrules were already fractionated to the formative stage of the original liquid droplets. Judging from the occurrence of manifoldly encountered chondrules in the Yamato (a) and Yamato (c) meteorites and abundant broken chondrules and chondrule fragments especially seen in Yamato (a), it is believed that the process of chondrule formation is due to a mechanism that produces a large quantity of droplets enough for frequent collisions with one another. Besides, varying chemical compositions of chondrules suggest that the parent materials of chondrules are probably heterogeneous in their chemical compositions.

2.2. *Metamorphism in the Yamato meteorites*

Meteorites frequently show various metamorphic textures originated from mechanical and thermal effects that the meteorites experienced after their forma-

tion (for example, LIPSCHUTZ and ANDERS, 1961; MARINGER and MANNING, 1962; RAMDOHR, 1963, 1973).

In the Yamato meteorites, olivine grains of all samples, except Yamato (b) lacking in olivine, exhibit more or less distinct undulatory extinction. Pyroxene and plagioclase in these meteorites show the same tendency. Partial melting of silicate phases is observed in both chondrules and matrices. One of the examples is the sheared and folded chondrule in the Yamato (a) meteorite, and the occurrence of minute droplets is observed as shown in Fig. 11 and Fig. 12 of Part 1. This peculiar feature is an exceptional structure that can not be found in other chondrules of Yamato (a), suggesting that only this chondrule experienced such strong stress before or during agglomeration. In the Yamato (d) meteorite, droplet-like silicate aggregates are observed around the phenocrystic olivine and pyroxene grains in the locally brecciated parts of the meteorite (Fig. 54 of Part 1). The same feature is found also in the matrix of the Yamato (g) meteorite. The silicate droplets fill the interstices of the olivine and pyroxene grains. The Yamato (g) meteorite contains some orthopyroxene grains associated with a kink band and clinopyroxene lamellae (Fig. 66 of Part 1). A kink band is frequently observed in highly strained minerals. A similar feature of orthopyroxene was found in enstatite of the Cumberland Falls, Norton County and Pena Blanca Spring enstatite achondrites (REID and COHEN, 1967). In these meteorites, kink bands in enstatite are composed of clinoenstatite which was formed by the stress-induced inversion from host enstatite. In the Yamato (g) meteorite, the kink band in the bronzite grain is formed by local deformation of the grain, and wedge-shaped lamellae of clinopyroxene develop along the kink band. The lamellae were probably produced by stress-induced deformation. Globules of fused metallic nickel-iron and troilite, associated with the partially melted silicate phase, are frequently found in stony meteorites (FISH *et al.*, 1960; RAMDOHR, 1963, 1973). They are also present in the Yamato (a), Yamato (d) and Yamato (g) meteorites. In the Yamato (a) meteorite, the globules are metallic nickel-iron (probably kamacite) and troilite, and their aggregates (Fig. 16 of Part 1); and the globules occur dispersed in the partially fused silicate phase. The globules are associated with myrmekitic intergrowth of troilite and metallic nickel-iron, and locally occur in discontinuous, thin veins extending from end to end of the meteorite section. Patches of fused silicate and fused silicate droplets are locally present in the myrmekitic veins. It is conspicuous that kamacite and troilite grains along the veins are fractured and broken into pieces.

In the Yamato (d) meteorite, troilite globules are collectively present in the interstices of the silicate grains in some parts of the meteorite (Fig. 51 of Part 1). In the Yamato (g) meteorite, thin opaque veins are observed to penetrate silicate grains and chondrules, and that minute opaque globules are scattered along the veins which are in contact with the slightly dark-colored silicate phase showing partial melting in appearance (Fig. 67 of Part 1). The mineral species of globules and veins could not be defined in the transmitted light. However, their occurrence is closely analogous to that of globules in the Yamato (a) and Yamato (d) meteor-

ites. It is supposed that these globular textures of opaque minerals were formed by local heating. These fused textures of opaque minerals in the Yamato (a), Yamato (d) and Yamato (g) meteorites are closely related to the mechanically induced phenomena probably by shock effect. However, the situation is different in the Yamato (c) and Yamato (b) meteorites. In the case of the Yamato (c) meteorite, the undulatory extinction of olivine is less distinct, and the melting phenomena and shock-induced veins are not found in the entire mass. However, the occurrence of a few orthopyroxene grains which were mechanically bent or sheared is conspicuous as shown in Fig. 45 of Part 1. The extremely deformed feature of orthopyroxene grains is in contrast to the less undulated extinction of olivine grains. A possible reason is that pyroxene crystals of elongated form were easily subjected to the mechanical deformation in the stage of the agglomeration of chondrite, because carbonaceous chondrite is characteristic of a mechanical mixture of minerals which were formed at different localities. According to MASON (1962a, 1963), most of hypersthene achondrites show a brecciated structure usually consisting of large bronzite crystals embedded in the matrix of finely fragmented bronzite grains. MASON (1963) suggested that the fragmented structure was formed under a considerable pressure in the agglomeration. The Yamato (b) meteorite as well as the Tatahouine bronzite achondrite (MASON, 1963) has not undergone so strong mechanical process as to yield brecciation, because of the equigranular structure and less distinct undulatory extinction of pyroxene. It has been supposed that the possible mechanical processes followed by shock effects were originated from the collision with the terrestrial surface in the meteorite fall and the preterrestrial disruption of the parent bodies of meteorite.

Mineralogy and structure of meteorites are considerably influenced by the so-called shock and pressure effects. Recently, the significance of the thermal effect on mineralogical and structural properties of chondritic meteorites was emphasized by DODD and VAN SCHMUS (1965), DODD *et al.* (1967) and VAN SCHMUS and WOOD (1967). Based on a series of structural and mineralogical changes seen in chondrites of a single subgroup, these authors considered that the chondrites with recrystallized texture and equilibrated mineral compositions were produced from the chondrites with unrecrystallized texture and unequilibrated mineral compositions by the sequential process of reheating after the chondrite agglomeration. The degree of metamorphism based on the petrographic features is rather qualitative, but the distribution patterns of iron and magnesium contents of olivine and calcium-poor pyroxene grains in individual meteorites can quantitatively show the degree of metamorphism. VAN SCHMUS and WOOD (1967) constructed a new classification of chondritic meteorites, combining the metamorphic degrees and the chemical groups of chondrites, E, H, L, LL and C groups. In these chondrite groups, only carbonaceous chondrites are essentially characteristic of unequilibrated ones, because carbonaceous chondrites have a character of a mixture of high-temperature components and low-temperature components. In comparison with the structural and mineralogical criteria of VAN SCHMUS and WOOD (1967), the Yamato (a) meteorite is prob-

ably an unequilibrated chondrite, because of its distinct chondritic structure, the opaque matrix and the presence of isotropic glass in chondrules. The Yamato (c) meteorite essentially belongs to the unequilibrated chondrite, because it is a carbonaceous chondrite. The Yamato (d) meteorite seems to be closer to an equilibrated chondrite, because of its crystalline matrix, the absence of glass in chondrules and the indistinct boundaries between chondrules and the matrix. The Yamato (g) meteorite is considered to be relatively equilibrated, but it is not so metamorphosed as the Yamato (d) meteorite, because the chondrule-matrix boundaries are more distinct than those of Yamato (d). However, the measurements of the distribution patterns of magnesium and iron contents of olivine and calcium-poor pyroxene grains in every Yamato meteorite sample are required for more accurate determination of equilibration degrees. The Yamato (a) meteorite contains glass in various stages of devitrification, although isotropic glass is also present. This fact is not necessarily consistent with one of the criteria by DODD and VAN SCHMUS (1965), that is, the presence of isotropic glass in chondrules of unequilibrated chondrites. The evidence of the Yamato (a) meteorite may support the idea of FREDRIKSSON (1963) and KEIL (1968), who proposed that the chemistry and mineralogy of chondrites had already been settled before the chondrite agglomeration, and who do not think much of the occurrence of thermal metamorphism. At present, it is still an open question whether meteorites experienced the metamorphic process due to reheating in the parent bodies.

3. Petrogenesis of the Yamato Meteorites

Enstatite chondrites consist of unique mineral constituents produced in an extremely reducing environment. As seen in the Yamato (a) meteorite, the occurrence of nearly pure enstatite, clinoenstatite and forsterite, niningerite, daubreelite, graphite and Si-bearing kamacite, and probable occurrence of oldhamite and sphalerite, are particularly significant. The presence of nearly iron-free silicate minerals suggests that iron is almost completely reduced to metal and sulfide. Cr, Mn, Mg and Ca which are lithophile in the usual terrestrial condition are present as sulfide minerals, daubreelite, niningerite, and oldhamite in the enstatite chondrites. Even a part of Si is reduced into metal, forming a solid solution with metallic nickel-iron. From this fact, the original environment of enstatite chondrites is supposed to be much more reducing than that of iron meteorites (MASON, 1966). On the other hand, it has been recognized that unrecrystallized or unequilibrated enstatite chondrites and recrystallized or equilibrated ones are present in the enstatite chondrite group (MASON, 1966; VAN SCHMUS and WOOD, 1967; KEIL, 1968). Three subgroups, unrecrystallized (type I) enstatite chondrites, intermediate type ones and recrystallized (type II) ones, were proposed by KEIL (1963). As discussed before, the Yamato (a) meteorite is probably placed in type I enstatite chondrite from the mineralogical and structural data. However, origins of the structural, mineralogical and chemical differences among the enstatite chondrites are still open to discussion as already pointed out by KEIL (1968).

In contrast with the enstatite chondrites formed under the highly reduced condition, the carbonaceous chondrites show several characteristics indicative of an oxidized environment. However, the carbonaceous chondrites are distinctly heterogeneous in mineralogical and chemical features. The carbonaceous chondrites contain several hydrated and oxide minerals, in addition to the reduced minerals such as troilite, pentlandite and native sulfur. For example, type I carbonaceous chondrites are composed of serpentine, montmorillonite, magnetite, epsomite, gypsum, magnesite, dolomite and limonite (DuFRESNE and ANDERS, 1962; MASON, 1962b; MUELLER, 1962; BOSTRÖM and FREDRIKSSON, 1966; KEIL, 1969; BASS, 1971). Type II chondrites contain serpentine, magnetite, epsomite and calcite (DuFRESNE and ANDERS, 1962; MASON, 1962b; KEIL, 1969). Type III carbonaceous chondrites include magnetite as seen in the Yamato (c) meteorite. Another unique chemical feature is that carbonaceous chondrites contain extraterrestrial organic compounds and that they hold higher contents of volatile elements. Indeed, the carbonaceous chondrite essentially shows a heterogeneous composition, because it contains both reduced minerals and oxidized ones and also both volatile materials and high-temperature silicate minerals in a single mass. Such heterogeneity was also found in the chemical compositions of mineral constituents. FREDRIKSSON and KEIL (1964) first showed varying compositional ranges of pyroxene and olivine in the Murray carbonaceous chondrite. The same tendency of pyroxene and olivine was later confirmed in other carbonaceous chondrites from type I to type III by WOOD (1967), REID *et al.* (1970) and CLARKE *et al.* (1970). These results suggest that the carbonaceous chondrites were formed by the mechanical assemblage of different materials from different localities at low temperature (FREDRIKSSON and KEIL, 1964; LARIMER and ANDERS, 1970). Mineralogical and chemical differences among type I, type II and type III are mainly dependent on the mixing ratios of high-temperature components and low-temperature ones (DODD *et al.*, 1967).

As illustrated in Fig. 2, distribution of individual chondrite groups is isolated in the specific region on the Urey-Craig diagram. This figure shows that olivine-bronzite chondrites (high-iron group chondrites) are originated from more oxidized environment than enstatite chondrites but less oxidized one than carbonaceous chondrites. WILLIAMS (1971) estimated that the temperature and oxygen partial pressure of the equilibrated ordinary chondrites were 900°C and 10^{-18} atm, assuming the equilibrium state among olivine, pyroxene and metallic iron. The result suggests much more oxidative environment of ordinary chondrites including olivine-bronzite chondrites in comparison with enstatite chondrites. In the present study, low-temperature plagioclase was found in the Yamato (g) olivine-bronzite chondrite. However, it has been usually noticed that the structural state of meteoritic plagioclase is in the high-temperature form (DUKE *et al.*, 1961; MIYASHIRO, 1962; MASON, 1965; VAN SCHMUS and RIBBE, 1968). Meteoritic plagioclase is a controversial problem. According to MIYASHIRO (1962), the common occurrence of high-temperature plagioclase directly suggests that chondritic meteorites bearing plagioclase were rapidly cooled from temperatures higher than 700°C, because high-temperature plagioclase is stably present at temperatures

higher than 700°C. On the other hand, VAN SCHMUS and RIBBE (1968) stated that the occurrence of high-temperature plagioclase was not necessarily related to the quenching of chondrites, and suggested that the disordered structure of plagioclase might be preserved during slow-cooling in the extremely dried environment. In the Yamato (g) meteorite, exsolution lamellae of clinopyroxene (probably pigeonite-type) parallel to (001) planes of host augite are preserved. According to POLDERVAART and HESS (1951) and HESS (1960), this kind of exsolution lamellae is produced above the orthopyroxene-pigeonite inversion temperature. If this is true, the coexistence of low-temperature plagioclase and Stillwater type exsolution phenomena of pyroxene suggests unequilibration of the Yamato (g) meteorite. However, there are several evidences indicating exsolution of clinopyroxene crystallizes out of host augite below the orthopyroxene-pigeonite inversion temperature (BOWN and GAY, 1960; BINNS *et al.*, 1963; YAMAGUCHI, 1973). According to YAMAGUCHI (1973), the exsolution phenomenon is caused by the lattice distortion of pyroxene. Indeed, the deformed structure of pyroxene and olivine is common in the Yamato (g) meteorite. Then, the presence of low-temperature plagioclase may suggest that the Yamato (g) meteorite experienced slow cooling.

Hypersthene achondrite is essentially composed of bronzite as seen in the Yamato (b) meteorite. RINGWOOD (1961) and MASON (1962a, 1967) suggested the sequential crystallization of the pallasite, hypersthene achondrite and pyroxene-plagioclase achondrite, assuming a melt composed of olivine-bronzite chondrite. In this process, metallic iron and olivine segregated in the early stage would form pallasite, and the subsequent process would produce hypersthene achondrite and pyroxene-plagioclase achondrite from the residual liquid approximately represented by the system silica-forsterite-anorthite of ANDERSEN (1915). Actually, MORGAN and LOVERING (1973) found the nearly equal amounts of Th and U in the Johnstown and Shalka hypersthene achondrites to those of ordinary chondrites. On the other hand, SCHNETZLER and PHILPOTTS (1969) explained the hypersthene achondrite as a cumulate of hypersthene crystals gravitationally separated from a melt of calcium-rich achondrite. In the Yamato (b) meteorite, it is supposed that the cooling rate was fairly fast because of the preservation of the partially devitrified glass, pale brown in color, and fluid inclusions in pyroxene grains.

Conclusion

As described above, the petrological investigations of the Yamato (a), Yamato (b), Yamato (c), Yamato (d) and Yamato (g) meteorites show the following results.

(1) The Yamato (a) meteorite is an enstatite chondrite with a distinctly chondritic structure, and it is composed of enstatite, clinoenstatite, olivine, cristobalite, plagioclase, glass, kamacite, graphite, schreibersite, perryite, troilite, daubreelite and niningerite. Oldhamite and sphalerite are probably present. The unique mineral composition suggests that this meteorite was formed in an extremely reducing environment. The meteorite shows a characteristic of unequilibrated chondrite of VAN SCHMUS and WOOD (1967), and may also be placed

in type I enstatite chondrite group of KEIL (1968). Several morphological and chemical features of chondrules in the Yamato (a) meteorite suggest that chondrules were formed by the rapid cooling of molten droplets, and that they experienced such mechanical processes as collision and destruction before or during their agglomeration into chondrite.

(2) The Yamato (b) meteorite is non-chondritic and essentially monomineralic, and is assigned to hypersthene achondrite of the Ca-poor achondrite group. Orthopyroxene (bronzite) is the only major mineral constituent. Clinopyroxene, tridymite, plagioclase, glass, chromite, metallic nickel-iron and troilite are present in accessory amounts.

(3) The Yamato (c) meteorite has a chondritic structure, and its mineralogical properties are characteristic of type III carbonaceous chondrite of WILK (1956). This meteorite is composed of olivine, orthopyroxene, clinopyroxene, plagioclase, magnetite, pentlandite, troilite and ilmenite. The presence of a considerable amount of magnetite accounts for the strongly magnetic property of this meteorite, and also suggests that this meteorite experienced the oxidized environment.

(4) The Yamato (d) meteorite is chondritic, and is composed mainly of olivine, orthopyroxene (bronzite), metallic nickel iron (kamacite and taenite) and troilite. Accessory mineral constituents are clinopyroxene, plagioclase, native copper and chromite. This meteorite is assigned to olivine-bronzite chondrite.

(5) The Yamato (g) meteorite is also chondritic, and its silicate phases are composed mainly of olivine and orthopyroxene (bronzite) with a small amount of plagioclase. Major minerals in the opaque phases are probably kamacite and taenite. Plagioclase in this meteorite is characteristic of a low-temperature structural state.

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References

- ALLEN, R. O. and B. MASON (1973): Minor and trace elements in some meteoritic minerals. *Geochim. Cosmochim. Acta*, **37**, 1435-1456.
- ANDERS, E. (1964): Origin, age and composition of meteorites. *Space Sci. Rev.*, **3**, 583-714.
- ANDERSEN, O. (1915): The system anorthite-forsterite-silica. *Am. J. Sci.*, **39**, 407-454.
- ANDERSEN, C. A., K. KEIL and B. MASON (1964): Silicon oxinitride, a meteoritic mineral. *Science*, **146**, 256-257.
- BASS, M. N. (1971): Montmorillonite and serpentine in Orgueil meteorite. *Geochim. Cosmochim. Acta*, **35**, 139-147.
- BINNS, R. A., J. V. P. LONG and S. J. B. REED (1963): Some naturally occurring members of the clinoenstatite-clinoferrosilite mineral series. *Nature*, **198**, 777-778.
- BLANDER, M. and M. ABDEL-GAWAD (1969): The origin of meteorites and the constrained equilibrium condensation theory. *Geochim. Cosmochim. Acta*, **33**, 701-716.
- BOSTRÖM, K. and K. FREDRIKSSON (1966): Surface conditions of the Orgueil meteorite parent

- body as indicated by mineral associations. *Smithonian Misc. Coll.*, **151**, 39 pp.
- BOWN, M. G. and P. GAY (1960): An X-ray study of exsolution phenomena in the Skaergaard pyroxenes. *Mineral. Mag.*, **32**, 379-388.
- BOYD, F. R. and J. L. ENGLAND (1965): The rhombic enstatite-clinoenstatite inversion. *Carnegie Inst. Wash. Year-book*, **64**, 117-120.
- CLARKE, R. S., E. JAROSEWICH, B. MASON, J. NELEN, M. GOMEZ and J. R. HYDE (1970): The Allende, Mexico, meteorite shower. *Smithonian Contrib. Earth Sci.*, **5**, 1-53.
- DODD, R. T. and W. R. VAN SCHMUS (1965): Significance of the unequilibrated ordinary chondrites. *J. Geophys. Res.*, **70**, 3801-3811.
- DODD, R. T., W. R. VAN SCHMUS and D. M. KOFFMAN (1967): A survey of the unequilibrated ordinary chondrites. *Geochim. Cosmochim. Acta*, **31**, 921-951.
- DUFRESNE, E. R. and E. ANDERS (1962): Chemical evolution of the carbonaceous chondrites. *Geochim. Cosmochim. Acta*, **26**, 1085-1114.
- DUKE, M. B., D. MAYNES and H. BROWN (1961): The petrography and chemical composition of the Bruderheim meteorite. *J. Geophys. Res.*, **66**, 3557-3563.
- FEHLING, J. and E. SHEIL (1962): Untersuchung der Unterkühlbarkeit von Metallschmelzen. *Z. Metallkde.*, **53**, 593-600.
- FISH, R. A., G. G. GOLES and E. ANDERS (1960): The record in meteorites. III. On the development of meteorites in asteroidal bodies. *Astrophys. J.*, **132**, 243-258.
- FREDRIKSSON, K. (1963): Chondrules and the meteorite parent bodies. *Trans. N. Y. Acad. Sci.*, Ser. 2, **25**, 756-769.
- FREDRIKSSON, K. and K. KEIL (1964): The iron, magnesium, calcium and nickel distribution in the Murray carbonaceous chondrite. *Meteoritics*, **2**, 201-217.
- FREDRIKSSON, K. and A. M. REID (1965): A chondrule in Chainpur meteorite. *Science*, **149**, 856-860.
- HESS, H. H. (1960): Stillwater igneous complex, Montana. *Geol. Soc. Am., Mem.*, **80**, 230 pp.
- HINTENBERGER, H., K. P. JOCHUM and M. SEUFERT (1973): The concentration of the trace elements W, Re, Os, Ir, Pt, Au, Hg, Tl, Pb, Bi, Th and U in the four recently found Antarctic meteorites Yamato (a), (b), (c) and (d), and in the meteorites Orgueil, Allende, Abec, Alegan and Johnstown. 36th Meteoritical Soc. Meeting at Davos.
- KEIL, K. (1968): Mineralogical and chemical relationships among enstatite chondrites. *J. Geophys. Res.*, **73**, 6945-6976.
- KEIL, K. (1969): Meteorite Composition. *Handbook of Geochemistry* (Wedepohl, K. H. ed.), Vol. I, 78-115, Springer, Berlin.
- KEIL, K. and C. A. ANDERSEN (1965): Electron microprobe study of the Jajh deh Kot Lalu enstatite chondrite. *Geochim. Cosmochim. Acta*, **29**, 621-632.
- KEIL, K. and K. FREDRIKSSON (1964): The Fe, Mg and Ca distribution in coexisting olivines and rhombic pyroxenes in chondrites. *J. Geophys. Res.*, **69**, 3487-3515.
- LARIMER, J. W. and E. ANDERS (1970): Chemical fractionations in meteorites-III. Major element fractionations in chondrites. *Geochim. Cosmochim. Acta*, **34**, 367-387.
- LIPSCHUTZ, M. E. and E. ANDERS (1961): Origin of diamonds in iron meteorites. *Geochim. Cosmochim. Acta*, **24**, 83-105.
- MARINGER, R. E. and G. K. MANNING (1962): Some observations on deformation and thermal alteration in meteoritic iron. *Researches on Meteorites* (Moore, C. B. ed.), pp. 123-144, Wiley, New York.
- MASON, B. (1962a): *Meteorites*, Wiley, 274 pp., New York.
- MASON, B. (1962b): The carbonaceous chondrites. *Space Sci. Rev.*, **1**, 621-646.
- MASON, B. (1963): The hypersthene achondrites. *Am. Mus. Novitates*, **2155**, 13 pp.

- MASON, B. (1965): Feldspar in chondrites. *Science*, **148**, 943.
- MASON, B. (1966): The enstatite chondrites. *Geochim. Cosmochim. Acta*, **30**, 23-39.
- MASON, B. (1967): The Bununu meteorite, and a discussion of the pyroxene-plagioclase achondrites. *Geochim. Cosmochim. Acta*, **31**, 107-115.
- MIYASHIRO, A. (1962): Common occurrence of high-temperature plagioclase in chondrites. *Jap. J. Geol. Geogr.*, **33**, 235-237.
- MORGAN, J. W. and J. F. LOVERING (1973): Uranium and thorium in achondrites. *Geochim. Cosmochim. Acta*, **37**, 1697-1707.
- MUELLER, G. (1962): Interpretation of micro-structures in carbonaceous meteorites. *Nature*, **196**, 929-932.
- POLDERVAART, A. and H. H. HESS (1951): Pyroxenes in the crystallization of basaltic magma. *J. Geol.*, **59**, 472-489.
- PRIOR, G. T. (1916): The meteoritic stones of Launton, Warbreccan, Cronstad, Daniel's Kuil, Khairpur and Sokobanja. *Mineral. Mag.*, **18**, 1-25.
- PRIOR, G. T. (1920): The classification of meteorites. *Mineral. Mag.*, **19**, 51-63.
- RAMDOHR, P. (1963): The opaque minerals in stony meteorites. *J. Geophys. Res.*, **68**, 2011-2036.
- RAMDOHR, P. (1973): *The Opaque Minerals in Stony Meteorites*, 245 pp., Akademie, Berlin.
- REED, G. B., K. KIGOSHI and A. TURKEVICH (1960): Determination of concentrations of heavy elements in meteorites by activation analysis. *Geochim. Cosmochim. Acta*, **20**, 122-140.
- REID, A. M., M. N. BASS, H. FUJITA, J. F. KERRIDGE and K. FREDRIKSSON (1970): Olivine and pyroxene in the Orgueil meteorite. *Geochim. Cosmochim. Acta*, **34**, 1253-1255.
- REID, A. M. and A. J. COHEN (1967): Some characteristics of enstatite from enstatite achondrites. *Geochim. Cosmochim. Acta*, **31**, 661-672.
- REID, A. M. and K. FREDRIKSSON (1967): Chondrules and Chondrites. *Researches in Geochemistry* (Abelson, P. H. ed.), **2**, 170-203, Wiley, New York.
- RINGWOOD, A. E. (1960): Silicon in metal phase of enstatite chondrites. *Nature*, **186**, 465-466.
- RINGWOOD, A. E. (1961): Chemical and genetic relationships among meteorites. *Geochim. Cosmochim. Acta*, **24**, 159-197.
- SCHNETZLER, C. C. and J. A. PHILPOTTS (1969): Genesis of the calcium-rich achondrites in light of rare-earth and barium concentrations. *Meteorite Research* (Millman, P. M. ed.), 206-216, Dordrecht, Reidel.
- SORBY, H. C. (1877): On the structure and origin of meteorites. *Nature*, **15**, 495-498.
- VAN SCHMUS, W. R. and P. H. RIBBE (1963): The composition and structural state of feldspar from chondritic meteorites. *Geochim. Cosmochim. Acta*, **32**, 1327-1342.
- VAN SCHMUS, W. R. and J. A. WOOD (1967): A chemical-petrologic classification for the chondritic meteorites. *Geochim. Cosmochim. Acta*, **31**, 747-765.
- WIK, H. B. (1956): The chemical composition of some stony meteorites. *Geochim. Cosmochim. Acta*, **9**, 279-289.
- WILLIAMS, R. J. (1971): Equilibrium temperatures, pressures and oxygen fugacities of the equilibrated chondrites. *Geochim. Cosmochim. Acta*, **35**, 407-411.
- WOOD, J. A. (1963): Origin of chondrules and chondrites. *Icarus*, **2**, 152-180.
- WOOD, J. A. (1967): Olivine and pyroxene compositions in type II carbonaceous chondrites. *Geochim. Cosmochim. Acta*, **31**, 2095-2108.
- YAMAGUCHI, Y. (1973): Study on the exsolution phenomena of pyroxenes. *J. Fac. Sci. Hokkaido Univ. Ser. IV, Geol. Mineral.*, **16**, 133-166.

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